The National Center for Photovoltaics Process Integration Project

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ABSTRACT

The research staff of the National Center for Photovoltaics (NCPV) has excelled in increasing solar cell efficiencies and advancing the understanding of photovoltaic-related materials and devices using their existing deposition, processing, and characterization tool base. However, using our existing equipment, it is becoming increasingly difficult to gain new knowledge about important issues related to process sequencing, growth chemistry and kinetics, interface characteristics, and the understanding of how these interfaces affect device performance. This difficulty is due in part to the state of our existing tool set, which lacks sufficient in-situ or real-time measurement capabilities, or lacks access to analytical tools where the sample remains in a controlled environment between deposition or processing and measurement. The existing tool set is difficult to upgrade with these capabilities because they are mostly "stand-alone," which means that they operate independently of each other and without a common substrate size or type. As a result, the NCPV has embarked on a project to provide the infrastructure to allow researchers to gain new knowledge that is difficult—if not impossible—to obtain with existing equipment. This infrastructure consists of providing flexible and robust integration of deposition, processing, and characterization tools via a standardized transfer interface such that samples move between tools in a controlled ambient. Standardization of control and data management software will enhance the utility of the integrated tools. This concept will also require the cooperation of experts from various material technologies and characterization disciplines to work directly with each other to obtain answers to key scientific and technological questions. Ultimately, it will be this synergistic effort between NREL staff, universities, and the photovoltaic (PV) industry around an integrated tool base that will add to the knowledge base, helping move many PV technologies forward.

INTRODUCTION

The NCPV has realized the need for more integrated tools for many years.[1] The III-V group at National Renewable Energy Laboratory (NREL) has successfully used an integrated metal-organic chemical vapor deposition (MOCVD) chamber, a molecular-beam epitaxy (MBE) chamber, and a surface science chamber for a number of years. By having integrated deposition and characterization and being able to transfer samples between chambers under ultra-high vacuum (UHV), researchers have been able to investigate the stability of surfaces[2] and surface reconstruction processes,[3] among other things. However, these tools are not integrated with other tools within the NCPV, nor does their tool design facilitate the needs of many of the other PV technologies. The PV program within NREL has advanced through focused efforts in materials growth and processing, development of novel device design, and the measurement and characterization of materials and devices. However, the continued success of the PV program will require the full integration of these research areas.

Process integration has been the key to the rapid advancement of the integrated circuit industry, which works with similar materials at the PV industry.[4] In their case, the various manufacturers came together to develop tool standards and integration schemes that were shared across the industry. In this way, they were able to drive the direction of tool fabricators to meet the needs of the entire industry. This is not to say that they shared all their manufacturing details. A useful analogy might be that they shared kitchen designs, appliances, and ingredients, but not the recipes or family secrets. The integrated-circuit industry had two distinctive advantages in accomplishing their process integration: they handle only one type of material—silicon wafers—and they have much larger financial resources with which to influence tool development.

Other research groups also see the need for process integration within their laboratories. Researchers within the Environmental Molecular Sciences Laboratory at Pacific Northwest National Laboratory have developed a multitask and multiinstrument sample transfer system to integrate a wide range of synthesis and analysis instruments.[5] In their system, they mount samples to a platen that incorporates heating and measurement capabilities. Similar sample transport/probe/heater assemblies are used by researchers at Michigan Technology University,[6] whereas Michigan State University has developed a sample transport/probe assembly[7] and the Mississippi State University has developed a sample transport/heater assembly.[8] Researchers at the Han-Meitner-Institut in Berlin, Germany, have done an outstanding job of not only designing a sample platen, but also, integrating an MOCVD and remote UHV chambers by transporting samples via a mobile UHV chamber.[9] This system is similar to the NREL III-V group's integrated tools, with the addition of being able to move samples to remote chambers. They have demonstrated that once they establish the correct handling procedure, they can avoid sample contamination completely.[10] However, all these systems use complex platen designs for small-area substrates that have been deemed impractical for NCPV research needs.

The main design goals of the NCPV Process Integration project are to (1) ensure a robust sample transport mechanism, (2) control the ambient of that sample transfer, (3) be able to deposit uniformly and reproducibly over areas that are big enough to be meaningful to industry, and (4) handle a wide variety of sample substrates.

THE PATH TO PROCESS INTEGRATION

To eventually build integrated tools, the NCPV will first design, construct, and test a prototype tool. This prototype tool consists of three major elements: a transport pod, a dock, and a thermal test chamber. This design will be refined and used to construct future tools so that they can be fully integrated. These future tools may be "stand-alone" or cluster tools with either robotic or track transport mechanisms (Figure 1), depending on the process and analytical needs of a given research area. If the platen is to be moved between tools, it is kept under a vacuum or inert gas while being moved from one tool to another. Standardizing robots and track transport mechanisms for cluster tools—along with heater designs—will also facilitate the construction of future tools. Researchers within the NCPV, as well as their university and industrial collaborators, will have access to these design standards; they can then build their tools so that they can be integrated to other tools and thus maximize the integrated tool collective.

Eventually, researchers will be able build modules to the standard, bring them to NREL, and be able to leverage their new experiment with the existing integrated tool base.

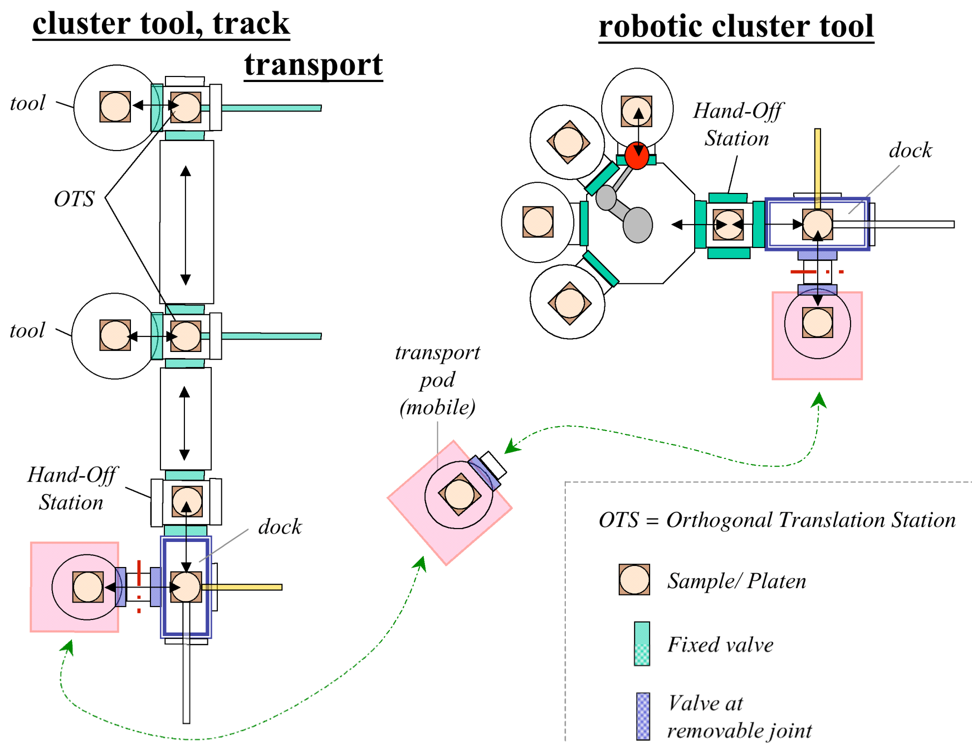

Figure 1: Relationship of the dock + pod protocol to potential future tool types. There are three potential arrangements for future tools: stand-alone tools (not shown), or cluster tools with either robotic or track transport mechanisms.

The component that moves from tool to tool is referred to as the transport pod in Figure 1. However, the dock + pod arrangement could be attached to the front end of an in-line grouping of tools or a cluster tool, as illustrated in the schematics in Figure 1. The transport pod will be used to move samples between these tools. The dock is the design element that houses the transfer mechanism for introducing platens into either a tool arrangement or a transport pod. With the transfer mechanisms housed in the dock, both the stand-alone tools and transport pods are free of internal transfer mechanisms.

The platen drives the requirements for the entire design. Agreement by the various groups within the NCPV have set the maximum substrate size the platen can handle to be 6.18 in. X 6.18 in. (157 mm X 157 mm). While this size supports the silicon photovoltaic industry (having a "6-inch square" protocol in polycrystalline and a "6-inch round" protocol in single crystalline), this size also more than adequately supports the other technological areas studied by the NCPV. Various platen designs will need to accommodate a variety of different substrates, such as soda-lime glass, high-temperature glass (e.g., Corning 1737), crystalline wafers (e.g., Si, Ge, GaAs), thin stainless steel, ceramic, and exotic materials (e.g., plastics and thin foils). Individual researchers will be able to use platens that accommodate smaller (or multiple smaller) substrates, but must be able to accommodate the maximum size in their tool. The platen itself must be able to withstand 1000ºC; therefore, construction material will likely be molybdenum or Inconel or similar material.

Techniques that are being considered for integrated deposition capabilities include physical vapor deposition techniques (e.g., thermal, electron-beam, sputtering, pulsed-laser deposition), chemical-bath deposition, vapor-transport deposition, as well as chemical-vapor deposition (CVD) techniques (MOCVD, hot-wire CVD, and plasma-enhanced CVD). Techniques that are being considered for integrated analytical capabilities include scanning Auger electron spectrometry, X-ray and ultraviolet photoelectron spectrometry, scanning electron microscopy, cathodoluminescence, electron back-scattered diffraction, secondary-electron imaging, backscattered electron imaging, energy-dispersive spectroscopy, X-ray analysis, photoluminescence, time-resolved photoluminescence, Raman, radiofrequency photo-conductive decay, thin-film analyzer Auger electron spectrometry, scanning tunneling microscopy, atomic force microscopy, electron force microscopy, scanning capacitance microscopy, Fourier transform infrared spectroscopy, X-ray photoemission spectroscopy, and Kelvin probe measurements. Techniques that are being considered for integrated processing capabilities include ion-beam milling, laser and thermal annealing, rapid thermal annealing, and etching.

Finally, the integrated-circuit industry has learned that the integration of control and data acquisition software is important and time consuming.[11] Efforts to create "plug and play" integration of manufacturing tools and data are under way[12] and being addressed as a part of this project.

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